Identifying mid-water targets using the higher frequencies emitted by seismic sources of opportunity

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***Abstract*—Seismic sources are routinely employed by the oil and gas industry to identify hydrocarbon reserves beneath the seabed, and by researchers to image the sub-seabed for geophysics and to identify geo-hazards such as tsunami-generating areas. For mitigation purposes, it is paramount to identify animals in the water column, but they can be missed by surface observations (if they are diving or in bad weather) or by Passive Acoustic Monitoring (if they remain silent). For operational reasons, it is also important to know about any other sizeable objects below the water surface. Seismic sources emit high-amplitude broadband sounds, typically below 300 Hz, directed toward the seabed. They can also radiate energy up to 20 kHz into the water column, and it can be used as a "source of opportunity". We use these higher frequencies (between 500 Hz to 20 kHz) to investigate their potential in identifying a variety of mid-water targets, with data from surveys conducted in challenging environments (two in shallow waters, 7–25 m deep, one in deep water, >1,500 m deep) with seismic sources up to 4,500 cubic inches in volume. The shallow-water surveys used a fixed source and freely drifting buoys, whereas the deep-water survey used a towed source with passive acoustic monitoring (PAM) vessel closely follow the seismic vessel to record data. The time spreads of individual shots recorded and the SNR at frequencies between 20 Hz – 20 kHz were compared between the surveys. Based on target strengths of potential targets at different ranges, and on benchmarked models of acoustic propagation, 2-D plots of measured vs. expected levels can be used to detect "hidden" targets of different sizes (from 0.5 to 20 m). The analyses suggest that, at 500 Hz, it is possible to confidently detect mid-water targets within the exclusion zone, and potentially going much further, to as deep as 2 km and as far as 2 km from the source. This has important implications for real-time mitigation and protection of marine mammals, which can be detected even if they are submerged and silent.**

Keywords—seismic; mitigation; marine animals; propagation modelling; surveys; shallow waters; deep waters; ambient noise

I. Introduction

Seismic imaging of the sub-seabed is routinely done by the oil and gas industry, to identify hydrocarbon reservoirs (e.g. [1]), and by geophysical researchers, to map large geodynamic structures (from mid-ocean ridge magma chambers to subduction zones areas) [2], to understand fragile areas such as cold-water coral reefs, and to identify geo-hazards such as: pockmark fields or tsunami-generating subduction zones [3]. This is done by using sources of high-amplitude sound, aimed directly at the seabed and transmitting at low frequencies [4], typically below 300 Hz, to achieve deep penetration [5]. Whether the seismic sources are either seismic, or boomers or sparkers [1], they are highly controllable and repeatable at lower frequencies.

To prevent potentially adverse effects on marine life, caused by the acoustic energy emitted by these sources [6], much effort has been devoted to marine mammal mitigation, leading to several national and international regulations [7]. Often, during a survey, seismic operators are legally required to monitor for the presence of protected animals within specific ranges, generally 500 m from the source location [8]. This monitoring is achieved with visual observations by trained marine mammal observers, using binoculars or automated tools [9], and it is generally restricted to daylight conditions. In most cases, the visual observations are complemented with PAM at all times [10], [11], although non-vocalizing animals would not be detectable with PAM. The extension of seismic operations to shallower waters and more complex environments also adds the risk of encountering sizeable, submerged objects in some operations (e.g. submerged logs near shores). Is there a way to detect silent, mid-water targets by using seismic sources, already present and emitting, as "sources of opportunity"?

Seismic pulses are generally spaced several seconds apart (generally between 10 to 20 s), enabling good propagation over sizeable ranges. They are also temporally small, enabling good spatial resolution of the survey regions depending on the frequencies used in post-processing and analysis. Although most of their energy is directed toward the seabed, some of this energy is scattered back into the water column by the seabed and sub-seabed interfaces. Depending on source array design, the number of sources and their geometrical positioning, seismic sources are known to emit sound at frequencies up to 20 kHz [12], [13]. At these higher frequencies, these sources can no longer be considered to radiate energy as monopoles [14], and they present different frequency-dependent directivity patterns

[15]. Because these sources are designed to be efficient at low frequencies, their acoustic characteristics at higher frequencies might also vary with time, the location of individual sources in the array and environmental conditions such as wave motion and tide.

This paper aims at investigating the potential of seismic sources, particularly at high frequencies (> 1 kHz), to detect any mid-water target (with a strong focus on marine mammal protection). Data from three surveys are presented and analyzed in Section II, looking at signal repeatability, time spreads as ranges between source and receiver vary, and frequency contents compared to background noise in each area. Section III shows how these recorded signals can be used in practice, by modelling acoustic propagation in water, reflections at air and seabed interfaces, and scattering for a range of marine species. Section IV presents the results (using the active sonar equation) as regions of probable detection, quantifying how much a mid-water target is required to scatter sound to be detected above background levels at each frequency. Section V discusses the significance of this approach and how it will be used in further work.

II. DATA FROM SEISMIC SURVEYS

The three typical surveys discussed in this article are taken from a larger portfolio, giving access to different environments, different survey methodologies, and different potentials for mid-water targets at different ranges. The nature of these surveys means that only their characteristics directly relevant to this study can be presented in this article. All the three surveys were carried out in the last 5 years.

A. Shallow-Water Survey #1

This first survey was undertaken in an oceanic channel of depth less than 25 m, with decreasing bathymetry from a river mouth to the continental shelf. During the survey, the source location was fixed and six free-floating buoys with two hydrophones per buoy were deployed to measure the underwater acoustic field at different distances from the source. The buoys were allowed to drift with the tides (following approximately straight lines), and acoustic data from hydrophones was sampled at 88.2 kHz. The survey region was approximately circular, 13.5 km in diameter, enveloping the fixed source location. Over the survey time of 4 days, hydrophones gathered measurements of close to 795 seismic pulses with a repetition rate within the typical range of 10 s – 20 s. Three different seismic sources were used for the survey, with working volume ranging from a single 10 cubic inch source, to (approximately) 700-cubic inch array.

A typical raw signal recorded from a buoy in this survey is presented in Fig. 1. The figure shows a direct arrival of the seismic signal (high-amplitude peak at 0.1 s) through the water column and further reflections from the sea surface and seabed. In this case, this acoustic signal decays to the background levels generally within 0.5 s. The time between direct reception of a seismic shot and return to ambient levels was observed to vary slightly with the source volume. These values ranged between 0.1 to 0.6 s (smallest source) up to 0.5 – 1.4 s (largest sized array). The general trends showed that the time-spread is proportional to the volume of the seismic sources used, consistent with larger sources emitting higher acoustic pressures and the possibility for longer reverberation in the waveguide.

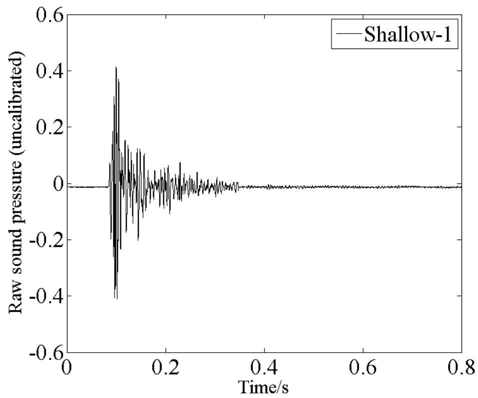

Fig. 1: Example time-spread of sound measured in shallow-water survey #1.

The choice of time-spread per pulse, during data processing, allows for the multiple reflections of acoustic signal emitted from the sources to be identified. These multiple reflections can come from the seabed, from the sea surface or even from a mid-water object before the next seismic shot is fired. These reflections and their subsequent propagation in the water column, travelling all the way to the receiver location, will vary with frequency, roughness and scattering strengths of the interfaces. Because these sources are optimized for lower frequencies (< 300 Hz), it is important to assess the frequency content of these signals up to 20 kHz, as recorded in the water column. Fig. 2 presents the averaged frequency content, between 20 Hz to 20 kHz, recorded in shallow water survey #1.

To derive the data shown in Fig. 2, a survey-dependent threshold value was applied to the acoustic measurements, to automatically detect seismic pulses with a good signal to noise ratio (SNR). Once a pulse was detected, the frequency content was evaluated and sorted into twelfth-octave frequency bands between 20 Hz and 20 kHz. Background ambient noise frequency content was evaluated in the same way, over equally long data segments (generally taken 2 s prior to the pulse). Averages and standard deviations shown in Fig. 2 illustrate that, even though a major portion of the signal energy emitted by the seismic source is contained in the frequency region between 100 Hz and 500 Hz, energy is also contained at frequencies beyond 500 Hz and in some cases up to 20 kHz. This implies that all components of the data, shown in Fig. 2, can be confidently used to detect reflections from potential mid-water targets. It should be noted that, prior to converting the individual raw data files into wav files (for processing in Matlab), any DC offset present in the recorded data was removed using Audacity™

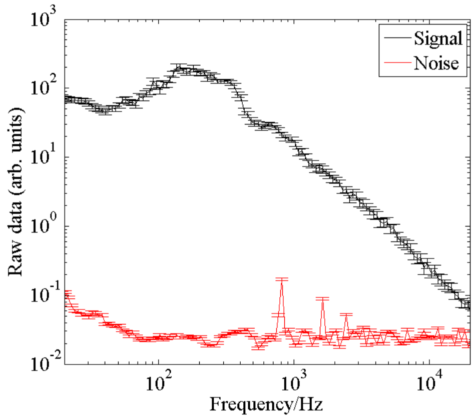

Fig. 2. Frequency-dependent amplitudes of signals (black) compared with background noise (red), for shallow-water survey #1. Note the very high signal-to-noise ratio at all frequencies.

The error bars as a function of frequency, as shown in Fig. 2, were extracted by evaluating the frequency content of 50 consecutively detected pulses. In this time, the receivers located under free-floating buoys would have travelled a distance of approximately 300 m along with the tide. Local water depth does not vary rapidly in this range [16], and thus the results shown in Fig. 2 can be considered as representative for this survey.

B. *Shallow-Water Survey #2*

The second shallow water survey used a source array of total approximate volume of 1800 cubic inches, with operating volumes increasing fractionally to the total, over four consecutive days. The data recording and processing methodology followed for this survey was the same as shallow-water survey #1. Water depth was within 10 m, up to a distance of 5 km from the fixed source location. The freely drifting buoys were allowed to drift in the survey region, covering a circular range, 10 km in diameter, centered on the fixed source location.

Fig. 3 presents a typical raw signal recorded from a buoy in this survey. The raw uncalibrated pressure values are much smaller than in shallow-water survey #1, and this can be attributed to the different distances between the source and receiver locations. There is also more reverberation in Fig. 3, than in Fig. 1. This is attributed to shallower depths and larger source volumes in survey #2. Time spreads for survey #2 varied between 0.6 to 1.3 s, with no particular dependence on source size but moderate dependence on receiver location. Fig. 4 shows an example of mean and standard deviations for signals and noise between 20 Hz and 20 kHz. The SNR is large enough up to 6 kHz to be useable for possible target detection.

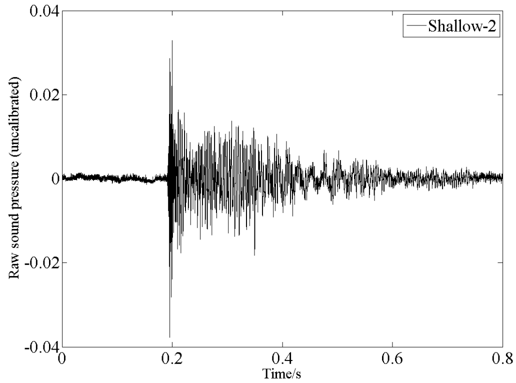

Fig. 3. Example time-spread of sound measured in shallow-water survey #2.

These limits, shown in Fig. 2 and Fig. 4, demonstrate the number of frequencies that can be considered for future processing and possible target detection in shallow water surveys. It should be noted that Fig. 2 and Fig. 4 represent statistical trends and the individual SNR tabulated at each frequency depend on various factors such as: instantaneous distance between source and receiver, bathymetry, local wind speeds and other environmental conditions, with higher frequencies attenuating faster than lower frequencies.

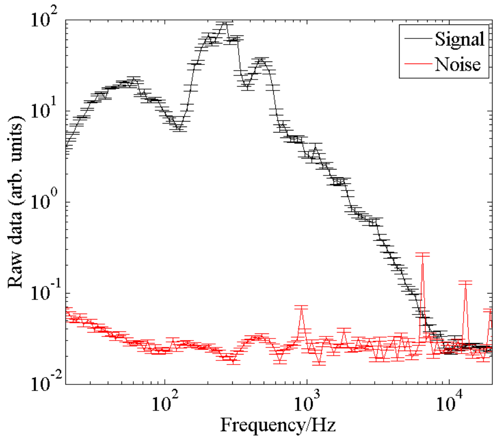

Fig. 4. Frequency-dependent amplitudes of signals (black) compared with background noise (red), for shallow-water survey #2. Note the

C. *Deep-Water Survey*

The third survey presented here was undertaken in deep water (depth > 1500 m). A seismic array of total volume approximately 4500 cubic inches was used as a source and was towed behind a primary vessel. A second PAM equipment vessel was positioned to closely follow the primary seismic vessel and was used for acoustic monitoring at a sampling frequency of 500 kHz. The data processing methodology followed for the deep water survey was the same as shallow-water surveys #1 and #2.

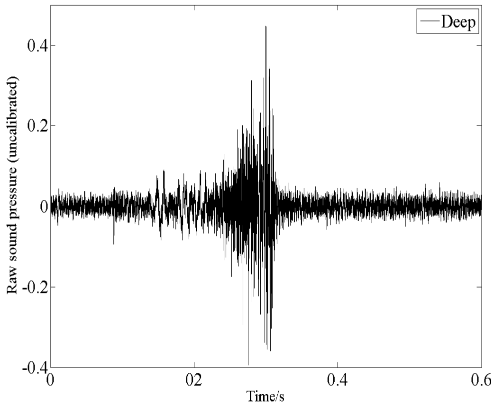

Fig. 5. Example time-spread of sound measured in the deep-water survey.

Fig. 5 presents an example of the typical raw signal recorded in the deep water survey. The general SNR of the recorded data, as shown in Fig. 6, is smaller than in the two shallow water surveys. This is also evident from the statistical trends of the frequency content of SNR shown in Fig. 6. By observing Fig. 5, i.e., by just using the time domain information, it is difficult to determine the direct path arrival. The usable frequency range for mid-water target detection, at frequencies beyond 500 Hz, is limited by the signal content above 5 kHz. However, the signal content between 500 Hz and 5 kHz is generally an order of magnitude higher than the noise content, causing a reduction in detection potential as frequency increases. Time-spread values for the deep water survey were very variable, between 0.6 and 1 s.

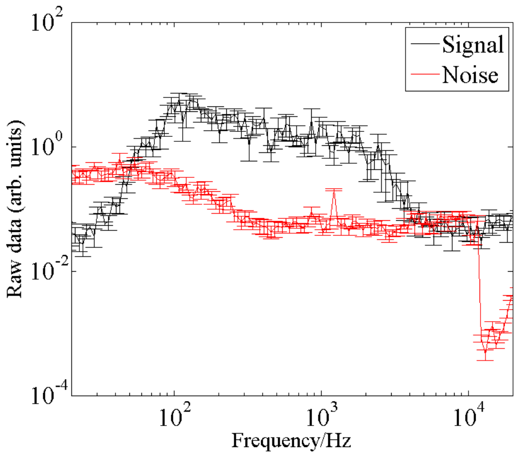

Fig. 6. Frequency-dependent amplitudes of signals (black) compared with background noise (red), for deep-water survey. Note the SNR is lower than the shallow-water surveys. Background noise is prevalent

These three very different surveys present constrain on the variation of recorded SNR with frequencies. This makes it possible to quantify the detectability of mid-water targets, using energy present in the signal above background noise, by defining spatial regions around the source location. The exact methodology, based on the active sonar equation, is presented in the following section.

III. Propagation and Scattering

The three very different surveys presented in this article demonstrate two important things: (1) the choice of time spread of the signals received after each seismic pulse for data processing has to be long enough so that, based on survey geometry and water depth, multiple reflections from the seabed, the sea surface and any object in-between is observable (also see [17]); and (2) the frequency content of the signal is broad enough that higher frequencies (enabling better spatial resolution) can be used, within the ranges selected, before the acoustic signal decays to background levels. Scattering at the seabed, or from any mid-water object, will also affect the amplitude of these reflections. Fig. 7 presents the typical 2D geometry of different possible returns for an acoustic signal emitted from a source into an ocean channel, demonstrating the travel paths to the receiver.

It must be noted that although Fig. 2, Fig. 4 and Fig. 6 show good detection possibilities of mid-water targets at frequencies beyond 1 kHz (based on SNR values), definite positive detection requires rigorous investigation of the recorded data in terms of ocean channel acoustic propagation [18] and identification of signal from background clutter. The variability of the output of seismic sources at high frequencies, generally influenced by the spacing between individual sources in an array, the local weather and wind patterns (which influences the relative positions of the array elements) and the bathymetry play a huge role in defining the received levels (RLs) at different frequencies [15]. Ray tracing simulations are generally employed for channel acoustic propagation [19] in deep water at frequencies of interest to this study (> 500 Hz). Estimating the ocean channel impulse response, seismic source directivity and employing different models for the seismic source(s) can be the important steps in creating a robust mathematical model to develop signal processing techniques for successful positive identification of mid-water targets.

The active sonar equation uses the source level (SL) or alternatively RL, corrected for spreading and attenuation (transmission loss TL), the noise level (NL) and the target strength (TS). Then, the detection threshold (DT) values for the targets of interest can be estimated using the actual operational conditions of the survey. This project’s emphasis on marine life mitigation/protection means most target strengths chosen correspond to typical marine mammals.

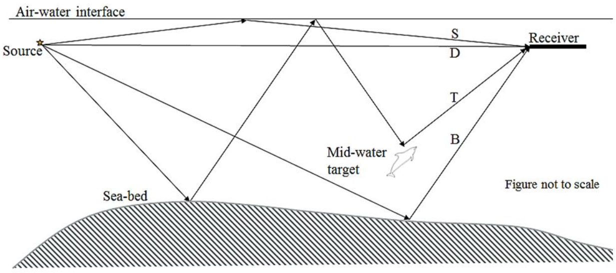

Fig. 7. Geometry for different propagation paths of an acoustic signal: direct arrival (path D), single scattering at the sea surface (path S), single scattering on the seabed (path B) or multiple scattering including a mid-water target (path T).

Source levels for the seismic sources (evaluated at 1 m distance) at different frequencies can either be considered from literature [20] or evaluated from received levels (RL) similar to those shown in Fig. 2. Target strength estimates for marine mammals and other objects can be taken from literature, for example as presented in references [21]. However, it should be noted that TS values for different marine mammals at the frequencies of interest are often limited and scarce. Their measurements also often vary with the aspect of the marine mammal studied, depth of target animal during observation [21] or age of the animal(s). Table 1 presents a few examples of TS values measured for different marine mammals as taken from literature. This table illustrates the difficulties in estimating TS of different mid-water targets of interest. However, in the case when no data on TS values of a marine mammal is available, approximate mathematical models [22] can sometimes be used for initial estimates.

Acoustic modelling software such as AcTUP [23] can be used to evaluate the one-way transmission loss (TL_1) from the source to the receiver location (either chosen or known). However, sometimes the two-way transmission loss ($TL = TL_1 + TL_2$) must also be considered. This includes either the case where the source and the receiver are placed very close to each other or when it is important to evaluate TL between a source and a mid-water target (distance R_1) and another TL between the mid-water target and the receiver (distance R_2). For this purpose, the region of interest for this study, arbitrarily defined as a 2 km x 2 km encompassing the entire water column, was divided into 1 m x 1 m square grids. Assuming that a potential mid-water target located in the column occupies a single 1 m x 1 m block, it is possible to evaluate the values of TL_1 and TL_2 based on R_1 and R_2, at each of the frequencies of interest. Theoretical attenuation curves for ocean water [1] at different frequencies were employed for this purpose. The cylindrical spreading loss of the acoustic energy based on values of R_1 and R_2 was also taken into consideration for evaluation of total TL. The total loss (transmission and spreading) using this model was observed to vary between 0 dB at the source/receiver location, and 67 dB at the edge of the chosen grid (depth and range 2 km each), for a frequency of 20 kHz. However, at 500 Hz, the total loss of acoustic energy at the edge of this grid was calculated to be 52 dB.

Table 1. Scattering strengths for some marine mammals selected on the basis of their importance in mitigation/protection.

Marine mammal	**TS (dB)**	**Frequency (kHz)**	**Scattering aspect**	**References**
Atlantic bottlenose dolphin	-11	23	Broadside	[24], [25]
Humpback whale	7	20	Broadside	[26]
Gray whale	-2.9	23	Tail	[27]
Sperm Whale	2.3 to 10.8	0.5 to 16	Not known	[28]

The results presented in Fig. 2 can be employed to evaluate the spatial variation of DT in the survey region. The lower limit for ocean noise can also be considered by using the noise spectra shown in Figure 13 from [29] (commonly known as Wenz curves). Considering the SNR of data recorded in the shallow-water survey #1 (Fig. 2), and looking at the two end members of the frequency region of interest (500 Hz and 20 kHz), the back-calculated SL values taken from the black curve of Fig. 2, after processing, respectively correspond to 230 dB and 170 dB re. 1 μPa. At these frequencies, NL values at the receiver locations were 160 dB and 167 dB re 1 μPa respectively (extracted from the red curve and assuming NL is uniform throughout the survey grid). By employing these SL and NL values, different values of estimated target strengths for mid-water objects between -30 dB to 30 dB, by evaluating the two-way Transmission Loss from the source to the receiver location (shown here for a source and receiver both 3 m deep) and assuming cylindrical spreading, the value of DT can be plotted on a 2 km x 2 km grid as a 2D plot covering the entire water column. Examples of these plots are presented and discussed in the next section.

IV. DETECTION OF MID-WATER TARGETS

Fig. 8 presents 4 different sub-plots showing the variation of DT values in the 2 km x 2 km spatial grid evaluated using the technique detailed in section III, for different TS values of mid-water targets at 20 kHz. The transition of 2D detectability region from blue (160 dB – high possibility) to red (0 dB – impossible) is based on the evaluation of the parameter (DT – NL). Hence, as the colors change from blue to red, the possibility of detection of a mid-water target of assumed TS values (as marked in sub-plots) slowly reduces. This trend in reduction of (DT – NL) with distance from the source(s) is obvious when employing a mid-water object with estimated TS value of –30 dB. From this sub-plot (bottom right of Fig. 8), it can be seen that the possibility of detection of mid-water target is only high at ranges/depths less than 100 m from the source/receiver location.

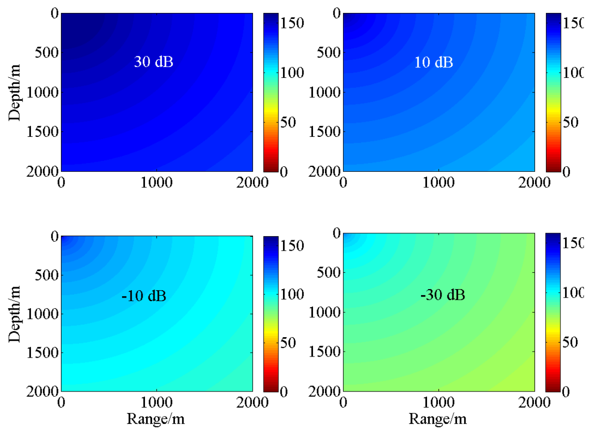

Fig. 8. Spatial regions for the possibility of detection (DT) for a mid-water target at TS values at 20 kHz. The maxima of the color bar represents (DT-NL) at 20 kHz. As region gets darker, the NL dominates RL and probability of detection reduces.

However, as the estimated TS value increase, the possibility of detection increases gradually and objects with TS of +30 dB could possibly be detected anywhere within the 2 km x 2 km grid with associated values SL = 170 dB and background NL = 160 dB (at 20 kHz). As frequency decreases, the SL increases (see Fig. 2) up to 230 dB at 500 Hz, and this larger SL implies increased possibility to detect marine mammals. It was observed that generating a plot similar to Fig. 8, when considering the active sonar equation for a frequency of 500 Hz, implied the possibility of detection of a mid-water target (of TS between –30 to 30 dB) at all points in the 2 x 2-km grid, anywhere in the water column.

Nevertheless, it must be noted (from Table 1), that underwater targets such are large marine mammals with TS value in the order of +30 dB at frequencies of interest (between 500 Hz to 20 kHz) to this study are very rare (and these values need to be further constrained). It is also known that TS values for marine mammals vary with age, sex, depth and type. Rigorous mathematical models of detection probabilities should therefore include this variability, and quantify the possible variations, accounting for regional differences in expected marine fauna.

V. CONCLUSIONS

This paper presents the first steps toward estimating the detectability of mid-water targets at different frequencies in 2D spatial regions encompassing the entire water column, using seismic sources as sources of opportunity. Data from three different surveys were presented (two shallow water and one deep water surveys). It was shown that the time-spread (or the amount of data required to be processed per pulse) depends on the type of survey and varied between 0.6 and 1.3 s. Since the intention of the work presented here was to employ the frequencies of opportunity emitted by a seismic source in the water column above 500 Hz, the signal to noise ratio of the received data in 1/12th octave frequency bands was evaluated and presented. It was shown that, regardless of the type of survey, there is enough energy available at the higher frequencies that could be used for a possible detection of mid-water targets. For estimating the DT values, the SL was estimated from the RL values recorded during the survey and TL was calculated from a mathematical model which employs ocean water acoustic absorption. Then, using different values of mid-water object TS values, considered in similar order of magnitude for large marine mammals, the possibility of detection was presented in the form on 2D geometrical plots. First analyses show that, at 500 Hz, it is possible to detect mid-water targets as deep as 2 km and as far as 2 km from the source.

It is also important to note that successful detection/identification of underwater targets ensonified by an acoustic source requires careful investigation of acoustical propagation in the survey region. Thus the impulse response of the acoustic channel (for specific source, receiver locations and survey geometry) at different frequencies will provide a concrete step towards this analysis. This impulse response has to be coupled with source modelling and directivity of the sources at higher frequencies, in order to develop a robust algorithm. This strategy forms the basis for future work within this project.

Finally, this project was conceived with the purpose of aiding PAM observers on board a seismic vessel, by providing additional information regarding the potential presence of “hidden, silent” marine mammals within the mitigation region, quantifying when it is possible or not possible to detect them. This work will ultimately lead to real-time mitigation system, using a variety of acoustic measurements at different ranges from the sources of opportunity.

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